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# USING TOTAL BETA-ACTIVITY MEASUREMENTS IN MILK TO DERIVE THYROID DOSES FROM CHERNOBYL FALLOUT

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**Following the Chernobyl accident, more than 200 childhood thyroid cancer cases have been observed in Brest Oblast of Belarus in territories slightly contaminated with $^{137}$Cs, but with suspected relatively high $^{131}$I fallout. The most helpful measurements available that can be used to estimate thyroid doses for the population of Brest Oblast are the total beta-activity measurements in cow's milk performed using DP-100 device within a few weeks after the accident. The $^{131}$I concentrations in milk were derived from the total beta-activity measurements on the basis of (1) a radioecological model used to estimate the variation with time of the radionuclide composition in milk and (2) the determination of the calibration factors of the DP-100 device for the most important radionuclides present in milk. As a result, $^{131}$I concentrations in milk were reconstructed for territories with different levels of $^{137}$Cs deposition. A non-linear dependence of the $^{131}$I concentration in milk on the $^{137}$Cs deposition density was obtained; it was used to estimate the thyroid doses from the consumption of $^{131}$I-contaminated cow's milk by the population of Brest Oblast. The average individual thyroid doses have been estimated to be 0.15, 0.18, 0.12, 0.06, 0.04 and 0.03 Gy for newborn, children aged 1, 5, 10 and 15 y and adults, respectively. The collective thyroid dose for the entire population of Brest Oblast is estimated to be 64,500 man Gy, the contribution from the adult population being about one half of the total. The methodology that is described could be applied in the framework of epidemiological studies of the relationship between radiation exposure to the thyroid gland and thyroid cancer in areas where numerous total beta-activity measurements in cow's milk were performed within a few weeks after the accident.**

## INTRODUCTION

Following the Chernobyl accident on April 26 1986, an increase in childhood thyroid cancer has been reported in different regions of Belarus(1). More than 200 thyroid cancer cases have been observed in Brest Oblast(2) in territories slightly contaminated with $^{137}$Cs from Chernobyl fallout, but with suspected relatively high $^{131}$I fallout(3). To carry out studies of the relationship between the radiation exposure of the thyroid glands and thyroid cancer, it is necessary to have reliable dose estimates. Dose reconstruction of internal exposure is most accurate when results of direct measurements of radionuclide contents in the body are used. Following the Chernobyl accident a large number of such measurements of $^{131}$I content in thyroid glands were performed in May–June 1986 mainly in the most contaminated Gomel and Mogilev Oblasts of Belarus and were used for thyroid dose reconstruction(4). However, results of measurements of $^{131}$I content in thyroid glands that may have been conducted in Brest Oblast are not available.

The best measurements that can be used for the reconstruction of internal thyroid doses from $^{131}$I in Brest Oblast are those of total beta-activity in cow's milk. At early times after the accident, the total beta-activity measurements were performed in the Sanitary and Hygiene Centers of the Ministry of Health, usually by means of Geiger–Mueller detectors, namely DP-100. Because this type of detector is not energy selective, the total beta-activities of the milk samples were obtained without any indication on the contributions of individual radionuclides.

The purposes of this paper are (1) to derive the $^{131}$I concentrations in milk from the total beta-activity measurements and (2) to estimate the thyroid doses resulting from the consumption of $^{131}$I-contaminated milk.

## METHODS AND RESULTS

### Determination of $^{131}$I in milk from the results of total beta-activity measurements

The measurements of total beta-activity using the DP-100 instrument were carried out by placing each milk sample in an aluminum dish placed in an organic glass support. Both the organic glass

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support with the sample and the gas end-window detector were placed in a lead cylindrical shielding. The size of the dish and the distance between the detector and the dish could be varied. For the measurements carried out in the Brest Oblast, the dish had an inner diameter of 40 mm and a depth of 10 mm; it was placed at a distance of 20 mm from the detector window.

The logbooks obtained from the Sanitary and Hygiene Centers list the results of the total beta-activity measurements in milk in 1986 and indicate that they were calculated using the following equation:

$$A_{\mathrm{hist}} = \left(P_{\mathrm{dev}} - P_{\mathrm{bg}}\right) \cdot \mathrm{CF}_{\mathrm{of}}, \tag{1}$$

where $A_{\mathrm{hist}}$ is the historical result of total beta-activity measurement, as listed in the logbooks (kBq $\mathrm{L}^{-1}$), $P_{\mathrm{dev}}$ is the count rate of device with milk sample (counts $\mathrm{min}^{-1}$), $P_{\mathrm{bg}}$ is the background count rate of device (counts $\mathrm{min}^{-1}$) and $\mathrm{CF}_{\mathrm{of}}$ is the calibration factor used in 1986 (kBq $\mathrm{L}^{-1}$ per count $\mathrm{min}^{-1}$).

According to an official document[5], the appropriate value of the calibration factor for the total beta-activity measurements in milk made in Brest Oblast shortly after the Chernobyl accident was $\mathrm{CF}_{\mathrm{of}} = 1.0$ kBq $\mathrm{L}^{-1}$ per count $\mathrm{min}^{-1}$. This value, which was used in 1986 to derive the total beta-activity from the count rate, was assumed to be independent of the time when the measurement was made. In fact, the radionuclide composition in milk varied according to time after deposition on the ground, leading to inaccuracies in the estimation of the total beta-activity. In order to improve the estimates of total beta-activity in milk, it is necessary to take into account the time-dependent radionuclide composition in milk and the calibration factors for the radionuclides that contribute most to the total beta-activity.

## Radionuclide composition in milk

To estimate the radionuclide composition in cow's milk, the fraction of the total activity due to each important radionuclide was calculated. The time-dependent activity fraction of radionuclide $i$ in cow's milk, $F_i(t)$, is

$$F_i(t) = \frac{A_i(t)}{A_{\mathrm{total}}(t)}. \tag{2}$$

where $A_i\,(t)$ is the activity of radionuclide $i$ in milk at time $t$ (kBq $\mathrm{L}^{-1}$) and $A_{\mathrm{total}}\,(t)$ is the total activity in milk at time $t$, (kBq $\mathrm{L}^{-1}$).

During the first few weeks after the accident, i.e. before $^{131}$I decayed to negligible levels, the contamination of milk resulted mainly from the consumption of contaminated pasture grass by cows. It was assumed in the calculations that the deposition of radionuclides on the ground occurred instantaneously and that cows had been put on pasture before the deposition occurred. The variation with time of the activity in cow's milk due to the consumption of radionuclide $i$ in pasture grass was calculated[6] as

$$A_i(t) = \sigma_i \cdot \frac{f_i}{Y} \cdot I_{\mathrm{g}} \cdot \mathrm{TF}_i \cdot \int_0^t \mathrm{e}^{-\left(\lambda_i^{\mathrm{w}}+\lambda_i^{\mathrm{r}}\right)\cdot\tau} \cdot \sum_{j=1}^{J_i} a_{i,j} \cdot \lambda_{i,j}^{m} \cdot \mathrm{e}^{-\left(\lambda_{i,j}^{m}+\lambda_i^{\mathrm{r}}\right)\cdot(t-\tau)}\mathrm{d}\tau, \tag{3}$$

where $\sigma_i$ is the ground deposition of radionuclide $i$ (kBq $\mathrm{m}^{-2}$), $f_i$ is the interception factor of radionuclide $i$ by grass (unitless), $Y$ is the yield of pasture grass at time of deposition (kg $\mathrm{m}^{-2}$), $I_{\mathrm{g}}$ is the daily intake of grass by cows (kg $\mathrm{d}^{-1}$), $\mathrm{TF}_i$ is the cow's intake-to-milk transfer factor (d $\mathrm{L}^{-1}$), $\lambda_i^{\mathrm{w}}$ is the loss of radionuclide activity by grass due to weathering and growth dilution ($\mathrm{d}^{-1}$), $J_i$ is the number of components $j$ of the function describing the retention of radionuclide $i$ in the cow's body, $a_{i,j}$ is the fraction of activity associated with component $j$, $\lambda_{i,j}^{m}$ is the biological transfer rate associated with component $j$ ($\mathrm{d}^{-1}$), $\lambda_i^{\mathrm{r}}$ is the radioactive decay constant of radionuclide $i$ ($\mathrm{d}^{-1}$) and $t$ is the time counted since deposition of fallout on the ground (d).

In the aftermath of the Chernobyl accident, the $^{137}$Cs deposition density on the ground is the only quantity that is well known and measured for all settlements of Belarus. Figure 1 shows the contamination pattern of Belarus by $^{137}$Cs and indicates the selected locations in Brest Oblast. The ground deposition of radionuclide $i$ was derived from the ground deposition of $^{137}$Cs as

$$\sigma_i = \sigma_{\mathrm{Cs137}} \cdot R_i, \tag{4}$$

where $\sigma_{\mathrm{Cs137}}$ is the ground deposition of $^{137}$Cs (kBq $\mathrm{m}^{-2}$) and $R_i$ is the ratio of activities of radionuclide $i$ and of $^{137}$Cs in ground deposition (unitless).

In the same manner, it is convenient to derive the value of the interception factor by grass of radionuclide $i$ from the corresponding value for $^{137}$Cs:

$$f_i = f_{\mathrm{Cs137}} \cdot R_{f,i}, \tag{5}$$

where $f_{\mathrm{Cs137}}$ is the interception factor of $^{137}$Cs by grass (unitless), $R_{f,j}$ is the ratio of interception factors for radionuclide $i$ and for $^{137}$Cs (unitless).

From Equations 2 to 5, the time-dependent fraction of the total activity in cow's milk due to radionuclide $i$ can be written in the following form:

$$F_i(t) = \frac{\mathrm{TF}_i \cdot R_i \cdot R_{f,i} \cdot \int_0^t \mathrm{e}^{-\left(\lambda_i^{\mathrm{w}}+\lambda_i^{\mathrm{r}}\right)\cdot\tau} \cdot \sum_{j=1}^{J_i} a_{i,j} \cdot \lambda_{i,j}^{m} \cdot \mathrm{e}^{-\left(\lambda_{i,j}^{m}+\lambda_i^{\mathrm{r}}\right)\cdot(t-\tau)}\mathrm{d}\tau}{\sum_i \mathrm{TF}_i \cdot R_i \cdot R_{f,i} \cdot \int_0^t \mathrm{e}^{-\left(\lambda_i^{\mathrm{w}}+\lambda_i^{\mathrm{r}}\right)\cdot\tau} \cdot \sum_{j=1}^{J_i} a_{i,j} \cdot \lambda_{i,j}^{m} \cdot \mathrm{e}^{-\left(\lambda_{i,j}^{m}+\lambda_i^{\mathrm{r}}\right)\cdot(t-\tau)}\mathrm{d}\tau}. \tag{6}$$

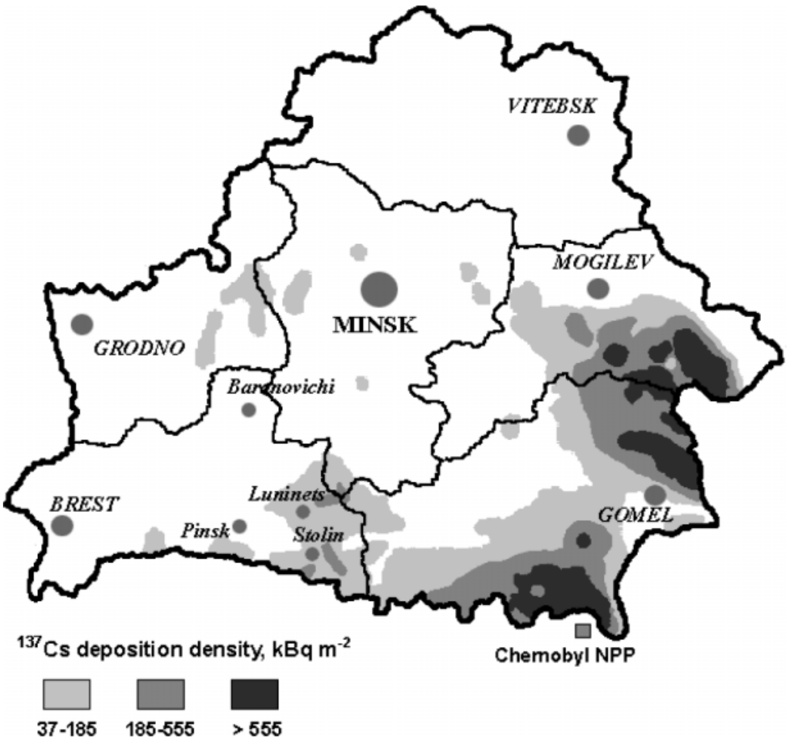


Figure 1. Map of the Republic of Belarus (State Committee on Hydrometeorology of Belarus, 1994) with indication of selected locations in Brest Oblast.

In the derivation of Equations 3 and 6, the simplifying assumption was made that the ground deposition of the radionuclides occurred instantaneously. In fact, as shown in Table 1 for three cities in Brest Oblast, the deposition of $^{131}$I on the ground took place over more than two weeks[7]. However, in each of the three cities, more than three quarters of the total $^{131}$I deposition occurred during 2 d—from 9:00 a.m. on 27 April till 9:00 a.m. on 29 April 1986. Because, as indicated later, the milk samples that were taken within 5 d after ground deposition were not taken into account, Equations 3 and 6 are precise enough to calculate the radionuclide concentrations in milk for the samples that were taken into consideration.

In the determination of the values of $R_i$ and $R_{f,i}$, it is important to take into account the type of radionuclide deposition (dry, wet, mixed) on the territory of the Brest Oblast and the available results of radiation monitoring:

- Data on daily precipitation collected at the meteorological stations of the Republic of Belarus show that the contamination of Brest Oblast mainly resulted from dry deposition (Table 1), and that light rain only occurred in some areas.
- The ratios of activities of radionuclide $i$ and of $^{137}$Cs in ground deposition, $R_i$, were taken from Minenko *et al.*[8] for all radionuclides except for $^{89}$Sr and $^{90}$Sr. For $^{90}$Sr, the ratio to $^{137}$Cs in ground deposition was estimated from activity measurements in soil performed after the accident in settlements in Brest Oblast[9]. For $^{89}$Sr, a ratio to $^{90}$Sr of 5.4 was used on the basis of measurements in soil[10].
- The values of the interception factor by grass depend on the radionuclide that is considered and on the type of deposition (dry, wet or mixed). For the dry deposition that was observed in the majority of locations in Brest Oblast, the contamination of grass depends on the deposition velocity, which depends in turn on the chemical form of the radionuclide. All radionuclides were in aerosol form, with the exception of the radioiodines. The ratio of the aerosol and gaseous (elemental and organic) fractions of the radioiodine activity was found to be in the range from 0.2 to 0.5 in different locations in Europe after the Chernobyl accident[11,12]. The deposition velocity onto vegetation for aerosol bound radionuclides is within an order of magnitude less than for elemental iodine and within an

**Table 1. Measured $^{131}$I daily fallout[7] and daily precipitation in selected locations in Brest Oblast.**

| Time interval, d/month (h) | $^{131}$I fallout (kBq m$^{-2}$) | | | Precipitation (mm) | | |
|---|---|---|---|---|---|---|
| | Brest | Baranovichi | Pinsk | Brest | Baranovichi | Pinsk |
| 25/4 (9 a.m.)–26/4 (9 a.m.) | 0.4 | 0.45 | 0.35 | 0 | 0 | 0 |
| 26/4 (9 a.m.)–27/4 (9 a.m.) | 15.2 | 25.0 | 2.8 | 0 | 0 | 0 |
| 27/4 (9 a.m.)–28/4 (9 a.m.) | 113.7 | 375.0 | 739.8 | 0 | 0.3 | 0.4 |
| 28/4 (9 a.m.)–29/4 (9 a.m.) | 37.3 | 160.4 | 184.6 | 0 | 0 | 0 |
| 29/4 (9 a.m.)–30/4 (9 a.m.) | 17.2 | 22.4 | 28.5 | 0 | 0 | 0 |
| 30/4 (9 a.m.)–1/5 (9 a.m.) | 6.6 | 3.9 | 13.0 | 0 | 0 | 0 |
| 1/5 (9 a.m.)–2/5(9 a.m.) | 1.8 | 3.2 | 5.1 | 0 | 0 | 0 |
| 2/5 (9 a.m.)–3/5(9 a.m.) | 0.4 | 1.5 | 4.1 | 0 | 0 | 0 |
| 3/5 (9 a.m.)–4/5(9 a.m.) | 0.55 | 0.77 | 2.2 | 0 | 0 | 0 |
| 4/5 (9 a.m.)–5/5(9 a.m.) | 0.64 | 0.75 | 1.1 | 0 | 0 | 0 |
| 5/5 (9 a.m.)–6/5(9 a.m.) | 0.21 | 0.75 | 0.93 | 0 | 0 | 0 |
| 6/5 (9 a.m.)–7/5(9 a.m.) | 0.04 | 0.6 | 1.0 | 0 | 0 | 0 |
| 7/5 (9 a.m.)–8/5(9 a.m.) | 0.3 | 0.6 | 0.52 | 0 | 0 | 0 |
| 8/5 (9 a.m.)–9/5(9 a.m.) | 1.7 | 2.1 | 4.6 | 0 | 0 | 0 |
| 9/5 (9 a.m.)–10/5(9 a.m.) | 0.47 | 1.4 | 1.1 | 0 | 0.3 | 1.4 |
| 10/5 (9 a.m.)–11/5(9 a.m.) | 1.2 | 1.5 | 3.7 | 8.0 | 0 | 0 |
| 11/5 (9 a.m.)–12/5(9 a.m.) | 0.2 | 1.2 | 0.75 | 6.1 | 4.7 | 0.6 |
| 12/5 (9 a.m.)–13/5(9 a.m.) | 0.23 | 0.08 | 0.73 | 0 | 0 | 0 |
| 13/5 (9 a.m.)–14/5(9 a.m.) | 0.13 | 0.23 | 0.49 | 0 | 0 | 0 |

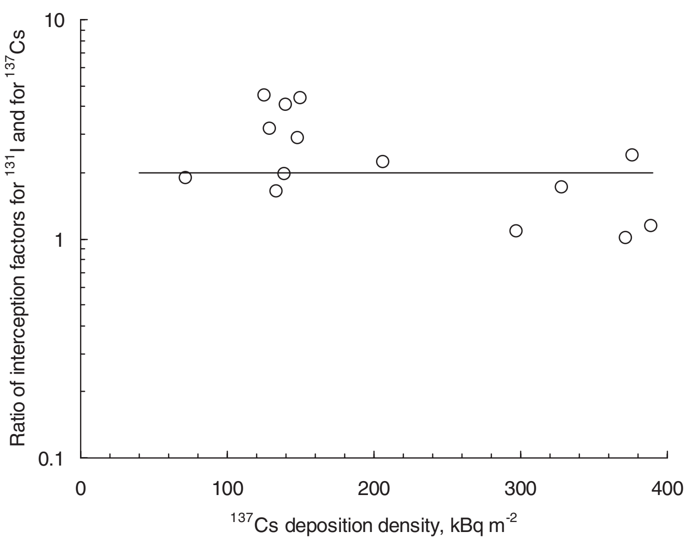


Figure 2. Ratio of interception factors for $^{131}$I and for $^{137}$Cs derived from soil and grass measurements in areas of dry deposition.

order of magnitude higher than for organic iodine[6]. The numerical value of the ratio of interception factors for iodine isotopes and for $^{137}$Cs was inferred from the results of measurements of $^{131}$I and $^{137}$Cs in soil and grass samples[13]. For dry deposition the ratio of interception factors for $^{131}$I and for $^{137}$Cs was estimated to be in the range from 1 to 4 with a median of ~2 (shown by thin line) (Figure 2). On that basis, the interception factor for dry deposited radioiodines was taken to be two times higher than that for $^{137}$Cs. For all other radionuclides the interception factors were taken to be equal to those for $^{137}$Cs.

**Table 2. Parameter values used to estimate the radionuclide composition in cow's milk[6,8–10,13–14].**

| Radionuclide | Parameter | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $R_i$ | $R_{f,i}$ | $TF_i$ | $\lambda_i^w$ | $a_{i,1}$ | $\lambda_{i,1}^m$ | $a_{i,2}$ | $\lambda_{i,2}^m$ |
| $^{131}I$ | 19 | 2 | $3 \times 10^{-3}$ | 0.067 | 1.0 | 0.99 | — | — |
| $^{133}I$ | 6.8 | 2 | $3 \times 10^{-3}$ | 0.067 | 1.0 | 0.99 | — | — |
| $^{134}Cs$ | 0.5 | 1 | $3 \times 10^{-3}$ | 0.047 | 0.8 | 0.46 | 0.2 | 0.046 |
| $^{136}Cs$ | 0.27 | 1 | $3 \times 10^{-3}$ | 0.047 | 0.8 | 0.46 | 0.2 | 0.046 |
| $^{137}Cs$ | 1.0 | 1 | $3 \times 10^{-3}$ | 0.047 | 0.8 | 0.46 | 0.2 | 0.046 |
| $^{89}Sr$ | 0.35 | 1 | $2 \times 10^{-3}$ | 0.047 | 0.9 | 0.23 | 0.1 | $6.9 \times 10^{-3}$ |
| $^{90}Sr$ | 0.06 | 1 | $2 \times 10^{-3}$ | 0.047 | 0.9 | 0.23 | 0.1 | $6.9 \times 10^{-3}$ |
| $^{103}Ru$ | 2.2 | 1 | $1 \times 10^{-4}$ | 0.047 | 0.1 | 0.023 | 0.9 | $6.9 \times 10^{-4}$ |
| $^{106}Ru$ | 0.86 | 1 | $1 \times 10^{-4}$ | 0.047 | 0.1 | 0.023 | 0.9 | $6.9 \times 10^{-4}$ |
| $^{140}Ba$ | 2.1 | 1 | $5 \times 10^{-4}$ | 0.047 | 0.9 | 0.23 | 0.1 | $6.9 \times 10^{-3}$ |
| $^{141}Ce$ | 0.63 | 1 | $2 \times 10^{-5}$ | 0.047 | 0.5 | 0.69 | 0.5 | 0.035 |
| $^{144}Ce$ | 0.49 | 1 | $2 \times 10^{-5}$ | 0.047 | 0.5 | 0.69 | 0.5 | 0.035 |

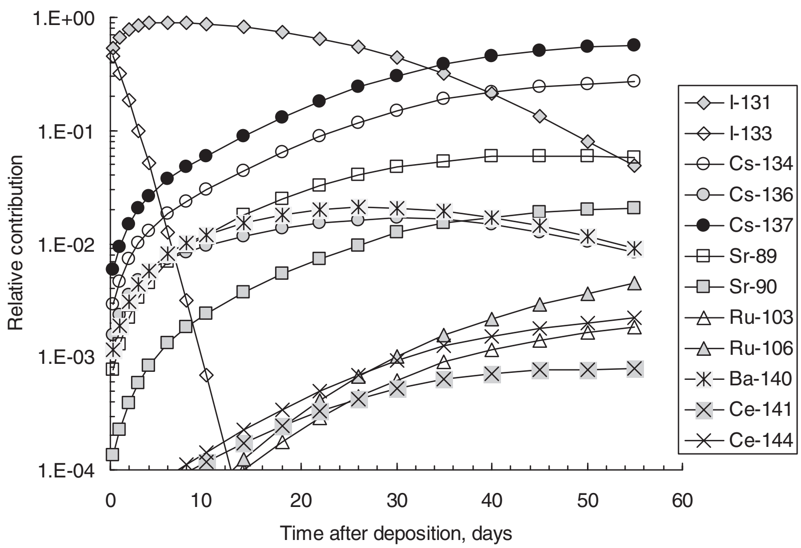


Figure 3. Relative contributions of a number of radionuclides to the total beta-activity in cow's milk (calculated for Brest Oblast).

With regard to the cow's intake-to-milk transfer factor, $TF_i$, values of $(3.0 \pm 2.6) \times 10^{-3}$ d L$^{-1}$ and $(3.0 \pm 1.9) \times 10^{-3}$ d L$^{-1}$ were used for iodine and caesium[13,14]. According to the same references[13,14], the rate of loss of activity by grass due to weathering and growth dilution was taken to be $\lambda_I^w = 0.067 \pm 0.016\,d^{-1}$ and $\lambda_{Cs}^w = 0.047 \pm 0.014\,d^{-1}$ for iodine and caesium isotopes, respectively. For the other radionuclides, the corresponding parameter values were taken from the literature[6].

The values of the parameters used to estimate the radionuclide composition in cow's milk are presented in Table 2.

Figure 3 shows the relative activity of the important radionuclides in cow's milk from Brest Oblast. Among the radionuclides that contributed >1% to the total activity in milk during the first few weeks after deposition, the most important are $^{131}I$, $^{137}Cs$, $^{134}Cs$, $^{89}Sr$ and $^{133}I$. During the first month after deposition, $^{131}I$ was the main contributor to the total activity concentration in milk. Later on, $^{137}Cs$, $^{134}Cs$, $^{89}Sr$ and $^{90}Sr$ became gradually more important than $^{131}I$.

### Assessment of the calibration factors of the detector

In the estimation procedure of the total beta-activity in milk that was used in 1986, only one value of calibration factor $CF_{of}$ was applied. This value was

**Table 3. Calibration factors $CF_i$ for DP-100 device[15].**

| | $^{131}I$ | $^{137}Cs$ | $^{134}Cs$ | $^{89}Sr$ | $^{90}Sr$ | $^{106}Ru$ | $^{144}Ce$ |
|---|---|---|---|---|---|---|---|
| $CF_i$ (kBq $L^{-1}$ per count $min^{-1}$) | 1.9 | 0.934 | 1.24 | 0.371 | 0.297 | 0.164 | 0.124 |

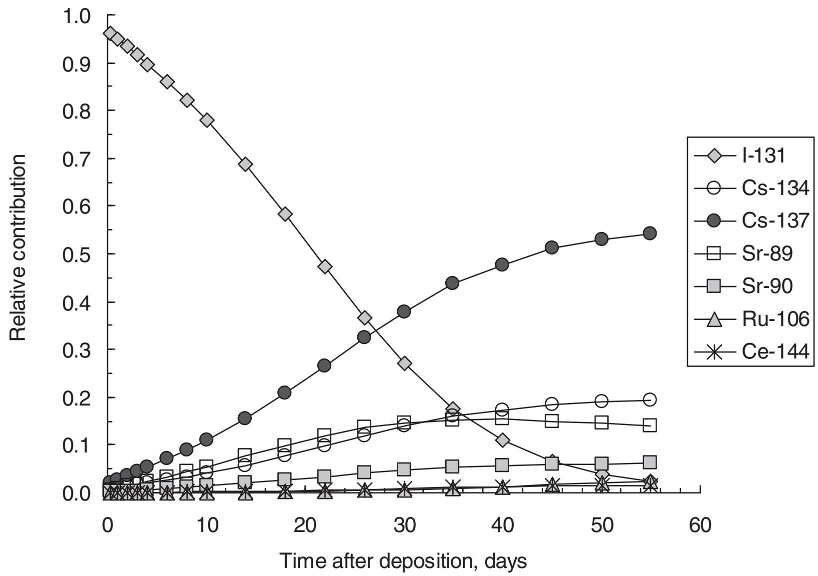


Figure 4. Relative contributions of a number of radionuclides to the DP-100 device response (calculated for Brest Oblast).

not either time-dependent or radionuclide specific. Later on, in 1992, a special investigation was performed to estimate radionuclide specific calibration factors for the DP-100 device[15]. The results, given in Table 3, were used to estimate, $DR_i(t)$, the time-dependent relative contributions to the detector response of the fraction of activity of each radionuclide $i$ in cow's milk. They are expressed as

$$DR_i(t) = \frac{P_i(t)}{\sum_i P_i(t)} \tag{7}$$

where $P_i(t) = F_i(t)/CF_i$ is the DP-100 device response to the fractional activity of radionuclide $i$ in cow's milk (counts $min^{-1}$ per kBq $L^{-1}$).

Figure 4 shows the variation with time of the relative contribution to the DP-100 device response of the fractional activities of the most important radionuclides in cow's milk. During the first three weeks after deposition, $^{131}I$ was the main contributor to the DP-100 device response. Later on, $^{137}Cs$, $^{134}Cs$ and $^{89}Sr$ became gradually more important than $^{131}I$.

It is important to note that the contributions to the DP-100 response of the activities in cow's milk of $^{133}I$, $^{136}Cs$, $^{103}Ru$, $^{140}Ba$ and $^{141}Ce$ were not considered because calibration factors are not available for those radionuclides. With the exception of $^{133}I$, these radionuclides did not contribute substantially to the activity in milk (see Figure 3). The contribution of $^{133}I$ was important during the first 5 d after deposition; the small number of measurements of total beta-activity in milk that were performed during those 5 d were excluded from this study.

## $^{131}$I concentration in milk

To derive the $^{131}I$ concentration in milk from the results of total beta-activity measurement, the following equation was used:

$$A_{I131}(T) = \frac{A_{hist}(T)}{CF_{of}} \cdot DR_{I131}(T) \cdot CF_{I131}, \tag{8}$$

where $A_{I131}(T)$ is the estimated $^{131}I$ concentration in milk at time $T$ (kBq $L^{-1}$), $A_{hist}(T)$ is the total beta-activity measured at time $T$ and reported in the logbooks (kBq $L^{-1}$), $DR_{I131}(T)$ is the relative contribution to the DP-100 device response of the $^{131}I$ activity in cow's milk at time $T$ calculated using Equation 7 (unitless) and $CF_{I131}$ is the calibration

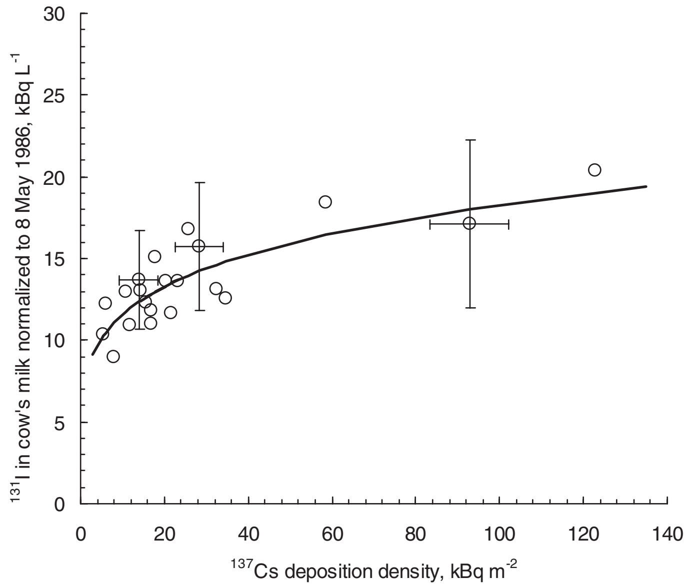


Figure 5. Means and standard deviations of the estimated $^{131}$I concentrations in cow's milk, normalised to 8 May, for a range of deposition densities. The open circles represent the estimated $^{131}$I concentrations; the solid curve was calculated using Equation 9.

factor for $^{131}$I in milk for DP-100 device (Bq g$^{-1}$ per count min$^{-1}$).

To compare the values of $^{131}$I concentration in milk, $A_{I131}(T)$, obtained at different times for different locations, those values were normalised to the same date of 8 May (10 d after deposition), using the time dependency given in Equation 3. Figure 5 shows the variation of the $^{131}$I concentrations in milk, normalised to 8 May, as a function of the $^{137}$Cs deposition density. Each point in Figure 5 is the mean value for one collective farm. The dependence of the $^{131}$I concentration in milk on the $^{137}$Cs deposition density is described by a purely empirical equation:

$$A_{I131} = 7.3 \cdot (\sigma_{Cs137})^{0.2}. \tag{9}$$

The correlation coefficient between the measured results and the values obtained using Equation 9 is $r = 0.82$.

As can be seen from Figure 5 the dependence of the $^{131}$I activity in milk on the $^{137}$Cs deposition density is non-linear. The same kind of curve describes the dependence of the $^{131}$I activity in milk on the $^{137}$Cs deposition density in contaminated regions of Russian Federation[16]. A similar non-linear dependence has been reported for the thyroid dose estimates based on the measurements of $^{131}$I content in thyroid glands in Gomel and Mogilev Oblasts in Belarus[4]. Taking into account that the thyroid dose is directly proportional to the concentration of $^{131}$I in milk, a non-linear dependence between thyroid dose and $^{137}$Cs deposition density also is observed in Brest Oblast.

## Thyroid doses from $^{131}$I intakes resulting from milk consumption

The consumption of locally produced milk was, for most individuals, the most important pathway for iodine intake by man. In comparison, the intake of radionuclides via consumption of leafy vegetables was much less important because, at the time of the radionuclide deposition on the ground, leafy vegetables were not ready for consumption even in the southern territories of Belarus.

In the aftermath of the Chernobyl accident, a number of countermeasures such as evacuation, temporary relocation and restriction on locally produced milk consumption were applied in the regions of Belarus that were highly contaminated with $^{137}$Cs. However, the contamination of the territory of Brest Oblast, which is located about 250 km to the west of the Chernobyl reactor site did not reach the level that would have triggered the implementation of administrative countermeasures.

Average individual thyroid doses due to $^{131}$I intake with milk were assessed for the inhabitants in Brest Oblast under the following conditions:

- constant daily rate of consumption of locally produced cow's milk;

- no delay between the production and the consumption of milk was taken for the rural inhabitants, while for people living in urban areas the delay from milking to consumption was taken to be 1 d;
- beginning of the pasture season before the time of main deposition of $^{131}$I on the ground.

The average thyroid dose for members of age group $k$ resulting from intakes of $^{131}$I with milk consumption has been estimated as:

$$D_k^{\mathrm{thyr,ing}} = \mathrm{TIA}_m \cdot V_k \cdot DF^{\mathrm{thyr,ing}} \tag{10}$$

where $D_k^{\mathrm{thyr,ing}}$ is the average thyroid dose for members of age group $k$ due to milk consumption (Gy), $\mathrm{TIA}_m$ is the time-integrated $^{131}$I activity concentration in milk (kBq d L$^{-1}$), $V_k$ is the milk consumption rate for age group $k$ (L d$^{-1}$) and $DF_k^{\mathrm{thyr,ing}}$ is the thyroid dose per unit intake of $^{131}$I by ingestion for age group $k$[17] (Gy kBq$^{-1}$).

It can be derived from Equation 3 that the time-integrated $^{131}$I activity in milk can be written in the following form: $\mathrm{TIA}_m = 25.9\ A_{\mathrm{I131}}$. From Equations 9 and 10, the average thyroid dose for members of age group $k$ can be estimated as

$$D_k^{\mathrm{thyr,ing}} = 190 \cdot \left(\sigma_{\mathrm{Cs137}}\right)^{0.2} \cdot V_k \cdot DF_k^{\mathrm{thyr,ing}}. \tag{11}$$

The values of the age-dependent parameters used in Equation 11 are given in Table 4. Taking into account the available information on the deposition density of $^{137}$Cs on the ground for each location in Brest Oblast in 1986 recalculated from Ref. (9), the average thyroid doses were estimated for population groups of different ages. The collective dose for the entire population of Brest Oblast was then assessed on the basis of the variation of the average individual thyroid dose with age, of the age distribution of the population and of the population size of each settlement in Brest Oblast available from the 1989 Census data.

The resulting estimates of age-dependent average individual thyroid doses and of collective thyroid doses to the population of Brest Oblast resulting from the consumption of $^{131}$I-contaminated milk are given in Table 5. As expected, the average thyroid

**Table 4. Age-dependent parameter values[14,17] used to calculate the thyroid doses according to Equation 11**

| Parameter | Age group of population (y) | | | | | |
|---|---|---|---|---|---|---|
| | 0 | 1 | 5 | 10 | 15 | 20 |
| $V_k$ (L d$^{-1}$) | 0.6 | 0.4 | 0.4 | 0.4 | 0.5 | 0.6 |
| $\mathrm{DF}_k^{\mathrm{thyr,ing}}$ (Gy kBq$^{-1}$) | $3.7 \times 10^{-3}$ | $3.6 \times 10^{-3}$ | $2.1 \times 10^{-3}$ | $1.0 \times 10^{-3}$ | $6.8 \times 10^{-4}$ | $4.3 \times 10^{-4}$ |

**Table 5. Age-dependent average individual thyroid doses and collective thyroid doses to the population of Brest Oblast resulting from the consumption of $^{131}$I-contaminated milk.**

| Thyroid dose | Age group (y) | | | | | | Average[c] |
|---|---|---|---|---|---|---|---|
| | 0[a] | 1 | 5 | 10 | 15 | 20 | |
| Individual (Gy) | | | | | | | |
| Luninets raion[b] | 0.27 | 0.31 | 0.21 | 0.10 | 0.07 | 0.06 | 0.08 |
| Pinsk raion[b] | 0.19 | 0.22 | 0.15 | 0.07 | 0.05 | 0.04 | 0.06 |
| Stolin raion[b] | 0.27 | 0.32 | 0.21 | 0.11 | 0.07 | 0.06 | 0.08 |
| Rest of Oblast | 0.13 | 0.15 | 0.10 | 0.05 | 0.03 | 0.03 | 0.04 |
| Entire Oblast | 0.15 | 0.18 | 0.12 | 0.06 | 0.04 | 0.03 | 0.05 |
| Collective, man Gy | | | | | | | |
| Luninets raion[b] | 360 | 420 | 1400 | 710 | 500 | 3210 | 6600 |
| Pinsk raion[b] | 590 | 680 | 2300 | 1100 | 800 | 5030 | 10,500 |
| Stolin raion[b] | 400 | 470 | 1550 | 780 | 550 | 3700 | 7450 |
| Rest of Oblast | 2250 | 2530 | 8450 | 4310 | 3050 | 19,360 | 39,950 |
| Entire Oblast | 3600 | 4100 | 13,700 | 6900 | 4900 | 31,300 | 64,500 |

(a)Assuming 6 months breast feeding for infants aged <1 y
(b)The most contaminated raions in Brest Oblast
(c)Population-weighted average

doses in Brest Oblast are found to decrease with age, being about 0.15, 0.18, 0.12, 0.06, 0.04 and 0.03 Gy, respectively, in the age groups of 0, 1, 5, 10, 15 y and adults. The collective thyroid dose for the entire population of Brest Oblast is estimated to be 64,500 man Gy, the contribution from the adult population being about one half of the total.

An excess absolute risk model assuming linear dose-response has been used to predict the number of expected thyroid cancers in Brest Oblast among persons aged up to 17 y at the time of exposure to $^{131}$I. The collective thyroid dose for this specific age group of population in Brest Oblast was estimated to be 33,200 man Gy (see Table 5). Assuming 70 y lifetime under the risk and applying the coefficient of excess absolute risk of 2.5 cases per $10^4$ PY Gy[18], from 400 to 900 radiation-induced thyroid cancer cases could be expected to develop among persons exposed in childhood and adolescence in Brest Oblast. The range in numbers of expected cases reflects the uncertainty in the dose estimates. This prediction was done without taking into account a reduction factor of 1/3 recommended by NCRP[18] for effectiveness of internal exposure from $^{131}$I intake in comparison with external exposure. Results recently published by Cardis *et al.*[19] show that the risk of radiation-induced thyroid cancer related to exposure to $^{131}$I in childhood and adolescence is similar to that from external radiation[20]. The risk of radiation-induced thyroid cancers among adults at time of exposure would be much smaller than that of children and adolescents.

### Uncertainties in dose estimates

The uncertainties associated with the estimates of age-dependent average individual thyroid doses arise from different sources. The most notable are likely to be as follows:

1. The uncertainties attached to the estimation of the $^{131}$I concentrations in milk on the basis of the total beta-activity measurements. In addition, there are fluctuations in the $^{131}$I concentration in cow's milk produced at the same location, as well as variability in dietary habits from one individual to another, and variability in the metabolic parameter values. These uncertainties are important when individuals are considered, but they are smoothed out to some extent when average values over the population of a raion are estimated.
2. The uncertainties attached to the assessment of the thyroid doses in the territories where measurements of total beta-activity in milk were not performed. The total beta-activity measurements from which the $^{131}$I concentrations in milk were derived were only carried out in a limited number of locations. Results from all other locations had to be extrapolated. This procedure is associated with uncertainties which cannot be easily quantified.

Within a specific settlement or age group, the individual doses are expected to show a significant variability that could reach up an order of magnitude or more. However, the uncertainty of average doses over the population of a raion is lower. It is subjectively estimated that the uncertainty associated with the estimation of average thyroid doses, or of collective doses, over the population of a given raion is a factor of 2–3 around the central estimate. The uncertainty associated with the estimation of the collective thyroid dose over the entire population of Brest Oblast would be somewhat smaller; it is subjectively estimated to be about a factor of 1.5–2 around the estimated average.

## CONCLUSIONS

An increase in childhood thyroid cancer was reported following the Chernobyl accident in different regions of Belarus. Among them, substantial number of thyroid cancer cases were observed in Brest Oblast, slightly contaminated with $^{137}$Cs from Chernobyl fallout, but with suspected relatively high $^{13}$I fallout. Because of the remoteness of Brest Oblast from Chernobyl NPP, sufficient radiation monitoring was performed in this region only after $^{131}$I had decayed to trivial levels. Therefore, a rather limited number of measurements were carried out after the accident in Brest Oblast that could be used for reconstruction of thyroid dose due to $^{131}$I intake. The total beta-activity measurements in cow's milk performed using DP-100 device within a few weeks after the accident might be considered as the most helpful measurements for that purpose. As this detector device is not energy selective, the total beta-activity of the milk sample was obtained in 1986, without any indication on the contributions of individual radionuclides from Chernobyl fallout.

In this study the $^{131}$I concentrations in milk were derived from the total beta-activity measurements on the basis of (1) a radioecological model used to estimate the time-dependent radionuclide composition in milk and (2) the determination of the calibration factors of the DP-100 device for the most important radionuclides present in milk. It was shown that during the first three weeks after deposition $^{131}$I was the main contributor to the total activity concentration in milk as well as to the DP-100 device response. Later on, $^{137}$Cs, $^{134}$Cs, $^{89}$Sr and $^{90}$Sr became gradually more important than $^{131}$I.

As a result, $^{131}$I concentrations in milk were reconstructed for territories with different levels of $^{137}$Cs deposition. A non-linear dependence of the $^{131}$I concentration in milk on the $^{137}$Cs deposition density was obtained. It was used to estimate thyroid dose from consumption of milk contaminated by $^{131}I$ for populations living in locations in Brest Oblast with different levels of fallouts. The average individual thyroid doses in Brest Oblast are found to be about 0.15, 0.18, 0.12, 0.06, 0.04 and 0.03 Gy, respectively, in the age groups of 0, 1, 5, 10, 15 y and adults. The collective thyroid dose for the entire population of Brest Oblast is estimated to be 64,500 man Gy, the contribution from the adult population being about one half of the total.

It is clear, however, that the $^{131}I$ thyroid doses derived from the results of total beta-activity measurements in milk are associated with larger uncertainties than those that would have been inferred from measurements of $^{131}I$ content in thyroid glands; unfortunately, such measurements are not available for Brest Oblast.

The results obtained show that total beta-activity measurements of cow's milk samples could be used for the thyroid dose reconstruction from the milk pathway for the populations affected following the Chernobyl accident.

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